Measurement of surface defects

The invention relates to a device for the inspection of surfaces as disclosed in the introductory part of claim 1, and to a method as disclosed in the introductory part of claim 13.

US 5,923,423 teaches the use of a device for the inspection of surfaces which includes a laser light source whose emitted beam is first split into two sub-beams in a beam splitter, one sub-beam being applied to a photodetector as a reference beam whereas the other beam is applied to the surface to be inspected as a measuring beam. The measuring beam has a direction which essentially opposes that of the surface movement. The light reflected by the surface is superposed on the reference beam in the further optical beam path (heterodyne detection). A space resolution detector (an array of, for example, photodiodes) provides the localization of surface defects on the surface. This requires very accurate adjustment of the detector relative to the surface. The resolution is limited by the detector, for example a CCD camera.

It is an object of the invention to enhance the measurement of contaminations or damage on surfaces.

The object is achieved in accordance with the invention by means of a device as disclosed in the characterizing part of claim 1, by means of a method as disclosed in the characterizing part of claim 13, and by means of an evaluation unit as disclosed in the characterizing part of claim 14. Reference is made to the claims 2 to 12 for advantageous further embodiments.

Because of the construction of the device in accordance with the invention, in which a detected defect is localized by way of a Doppler frequency shift, a speed that is determined therefrom, and an arithmetical determination of the position that is thus enabled, the location can be very accurately determined. This results in a very high resolution of the device that also enables the detection of small defects. Moreover, the speed of measurement is very high.

Defects occurring on the surface (for example, a particle resting thereon or a damage area that extends inwards (pinhole)), are irradiated in motion by the component of the light beam that extends in the direction thereof or in the opposite direction, so that the

frequency of the light that is reflected by the defect is changed relative to that of the applied
light. The use of the Doppler effect significantly simplifies the measurement of the location.
The detector need not satisfy very severe requirements. Moreover, the laser need not oscillate
in a defined mode either. The frequency shift that is induced between the applied light and

5   the reflected light by the speed of the defect lies in the range that can be readily measured,
that is, typically in a range of the order of magnitude of a few 10 kHz, thus facilitating the
evaluation.

The resolution is significantly finer than the size of the light spot. Therefore,
despite the desired high resolution a comparatively large light spot can be used so that the

10   time required for scanning the surface is reduced.

When an elliptical light spot is formed with a major axis that extends radially
in the case of a round or practically round wafer to be inspected, defects in different radial
positions on the surface to be inspected will traverse different regions of the light spot.
Because the defects that are situated further outwards in the radial direction have to travel a

15   distance per unit of time that is larger than that traveled by defects that are situated further
inwards, their speed is increased; this increase can be measured by way of the Doppler shift
of the frequency. The radial position of the defect can thus be localized. The invention thus
enables exact determination of the position of a detected defect by way of a velocity
measurement that is carried out on the basis of the Doppler frequency shift.

20   There is also envisaged detection of the instantaneous orientation of the
surface, for example, in a decoder associated with the rotary drive of the wafer, so that
additionally, for example, the angular position of a wafer can be determined upon detection
of a defect. The pole co-ordinates of the defect are thus fully known. Exact localization is
then possible.

25   Further advantages and details of the invention will become apparent from the
embodiments of the invention that are described in detail hereinafter with reference to the
drawing. In the drawing:

Fig. 1 is a diagrammatic overall representation of a first embodiment of a
device in accordance with the invention,

30   Fig. 2 is a side elevation of a sample holder,

Fig. 3 is a plan view of the surface to be inspected in which the trajectory of
the sample is also indicated,

Fig. 4 is a view similar to that of Fig. 3 with inserted cartesian and pole
co-ordinates of a surface defect,

Fig. 5 is a diagrammatic overall representation of a second embodiment of a device in accordance with the invention, and

Fig. 6 shows as a function of time the measuring signal that is formed in the device shown in Fig. 5.

5   The embodiment of the device that is shown in Fig. 1 includes a light source 1 which is preferably constructed as a laser light source because of the desired monochromaticity and the high intensity. However, the use of a laser light source is not absolutely necessary, since a beam splitter 4 that is arranged in the emitted beam 2 could also lead to interference of beams 5 and 6 split off from the original beam 2, that is, even in the

10   case of light rays of small coherence length only while the path is the same. Fig. 1 shows different path lengths of the reference beam 6 on the one side and the path length of the beam that acts on the surface 8 and of the light 15 deflected by this surface or by a defect 14 on the other side. In order to make interference of the reflected light 15 with the reference beam 6 also possible in such a case, long coherence lengths are required; such lengths are offered by

15   a laser.

The laser 1 continuously emits monochromatic light, that is, approximately in the visible range and typically of a wavelength of, for example, 488 nm. Even though use can be made of a light source with a shorter wavelength so as to improve the sensitivity, the scatter cross-section of the light with the air surrounding the surface then also increases.

20   Granted, measurement in a helium atmosphere or in vacuum conditions is also possible in theory, but would be very expensive.

A beam splitter 4 is arranged in the beam path of the beam emitted by the laser 1. The beam splitter may be constructed in various ways, for example as Fresnel's mirrors, as a double gap, as a combination of a polarizing optical cube and a $\lambda/2$ plate, or as another

25   known mechanism. In the present embodiment the light beam 2 is split into two beams 5, 6 only. However, it is also possible to split off further measuring beams 5 and to inspect, for example, a plurality of surfaces 8 simultaneously.

A semi-transparent mirror which constitutes a very simple and inexpensive component is used as the beam splitter 4 in the present embodiment.

30   The beam splitter 4 may be preceded by an optical system 3, for example a telescope with two cylindrical lenses. Magnification by the optical system 3 takes place in one plane only. The telescope 3 ensures that the beam splitter is uniformly illuminated within an essentially elliptical region, so that the light spot 9 arising beyond this region also has an elliptical contour; such an elliptical light spot extends in the radial direction of a round wafer

13 to be inspected and such a wafer could be provided with a cut-out to enhance the ease of handling.

The measuring beam 5 that is separated from the light beam 2 by the beam splitter 4 is applied to a further optical system 7 which includes a deflection mirror 7a and a focusing optical system 7b, for example a converging lens. Alternatively, or additionally to the lens 3, the converging lens 7 may also have a cylindrical construction in order to realize an elliptical light spot 9 on the surface 8. The optical system 7 applies the measuring beam 5 in a tangential direction at a flat angle of incidence α to the rotating surface 8 of the wafer 13 to be inspected, notably a silicon wafer that is provided with a coating or not, for example, a wafer for an optically and/or magnetically readable data carrier, thus forming a light spot 9 on this surface. In the present embodiment the beam is applied with a component S in the direction opposing the direction of rotation U of the wafer 13. Application with a component in the direction of rotation U is also possible.

The light spot 9 can be moved by means of a movable optical system, that is, in this case in the radial direction of the wafer 13 to be inspected, thus enabling complete scanning of the surface 8 thereof. It is particularly advantageous to keep the entire optical system that influences the incident beam 2 stationary instead and to make the wafer 13 perform, in addition to the rotary movement, a superposed translatory movement so that the spiral-like trajectory B of the object 13 as shown in Fig. 3 is obtained. The light spot 9 retains its position and the wafer 13 is moved underneath the light spot in such a manner that its surface 8 can be completely scanned.

In a first embodiment (Fig. 1) the reference beam 6 that is also formed in the beam splitter 4 from the beam 2 emitted by the light source 1 is applied without deflection (be it that this is not an absolute condition) to a semi-transparent mirror 30 in which a part 6a of the reference beam 6 is deflected and a further part 6b is rectilinearly applied to an entrance window of a detector 16.

The part 6a of the reference beam that is deflected by reflection in the mirror 30 is applied, via a further mirror 31, to an entrance window of a second detector 17 which may also be integrated with the first detector 16 so as to form one unit. Each of the entrance windows is preceded by a respective collimating optical system 16a, 17a that is shown in the form of a converging lens in the drawing.

The circular frequency ω of the inspected surface 8 is constant; therefore, any defects 14 present are passed underneath the light spot 9, that is, in the direction transversely of the major axis thereof, at a constant circular frequency ω. Depending on the radial position

of a defect 14, its speed of revolution differs, because for a particle that is situated further

outwards the speed of revolution

$$v = \omega r$$

(where r = radial distance between the defect 14 and the center)

5   is higher than for a defect that is situated further inwards.

The sample 13 is mounted on a sample holder 20. With the sample holder

there is associated a decoder for detecting its instantaneous position, in this case being an

angular position. When a defect 14 occurs, the relevant angle of rotation of the sample holder

20 can thus be determined upon the passage of the defect 14 through the light spot 9.

10   When a defect 14 occurs on the surface 8, the measuring beam 5 is scattered

thereby. The scattered light 15 is imaged, via an optical mirror system 32, in the mirror 33 so

as to be superposed with the reference beam 6, resulting in a time-modulated signal (Fig. 6)

with a constant component from the reference beam 6 and a temporally periodic component

from the reflected light 15. The optical system 32 should not have an excessively large

15   numerical aperture, because the Doppler frequency shift is dependent on the scatter angle. If

the scatter cone detected is too large, therefore, a significant widening of the measured

frequency occurs. The reflected light 15, superposed on the reference beam 6b, is applied to

the entrance gap of the first light-sensitive detector 16 by way of the optical system 16a. The

reference beam 6a is applied to the second detector 17. The detector 16, or the detectors 16,

20   17, need not detect in a space resolved mode. The noise of the laser, formed from the

reference beam 6 and detected by the detector 17, can be subtracted by comparison of the

input signals of the detector 16 and the detector 17. Only the temporally modulated

component then remains for evaluation; this results in a distinct signal waveform. A

component of this kind, comprising the detectors 16, 17, is also referred to as a noise

25   cancellation detector.

Because the superposed signal of the reflected light 15 and the reference beam

6b is modulated with the difference frequency resulting from the Doppler shift in the case of

occurrence of a defect 14, the acquisition of the measuring signal may also be such that only

signals that have the appropriate frequency are evaluated. For example, signals that are due to

30   scatter on air and do not have this frequency are thus filtered out. The measuring window can

be pre-adjusted in such a manner that it has limit frequencies in the form of difference

frequencies that correspond to the maximum outer position of a defect 14 on the wafer 13 and

difference frequencies that correspond to the maximum inner position of the defect 14 on the

wafer 13.

It will be evident that the light source 1, the surface 8 and the detectors 16, 17 can be arranged in a variety of ways that can be realized by selection of suitable deflection and converging optical systems. It is not necessary either, of course, that the light 2 is incident on the surface 8 from above; it may also be directed downwards or be oriented in a

5   different way. The detector 16 or the detectors 16, 17 are constructed as photoelectric detectors in known manner and hence convert a light signal into an electrical signal. Typically photodiodes can be used in the detectors 16, 17.

A second embodiment (Fig. 5) is provided with only one detector 16 in which a superposed signal from the reference beam 6 and the reflected light 15 is detected; this

10   results in the signal that is shown in Fig. 6 and that also constitutes the input signal for the detector 16 in the above version. As opposed to the first embodiment, however, no second detector 17 is provided for a reference beam 6a, so that no background suppression takes place in the detector 16. The time modulation of the signal, however, can be distinguished so that the frequency shift can be derived therefrom.

15   The function of the device 1 and the method in accordance with the invention will be explained on the basis of Fig. 1.

The measuring beam 5 that is formed in the beam splitter 4 is incident on the surface 8 within the light spot 9 that remains constant during the entire measurement.

In the case of an ideally smooth surface 8, the light is reflected (except for the

20   scattering on air molecules) subject to the reflection condition: angle of incidence = angle of exit. The light thus reflected is not incident on any of the entrance windows of the detector 16 or the detectors 16, 17. However, the detector 16 or 17 always receives a signal from the reference beam 6 or 6a or 6b.

When a defect 14 occurs, the incident light 2 is scattered thereby. The

25   scattered light 15 can be detected by way of the detector 16.

The position of the defect 14 on the surface can be very accurately determined even in the case of a stretched light spot 9, for example a light spot 9 that is elliptically stretched in such a manner that its major dimension extends radially with respect to the wafer; this is a central aspect of the invention: from the setting of the optical system that

30   guides the light beam 2 it is known where this beam is incident on the rotating wafer 13, that is, where the strip that is scanned by the light spot 9 is situated in the radial direction. When a signal occurs in a detector 16, the instantaneous angular position of the sample holder 20 is determined by way of the decoder.

To this end, the sample holder may be provided, for example, with an angular scale which is automatically read, by way of the decoder, at the instant of reception of a signal by at least one of the detectors 16, 17. Consequently, the angle of rotation φ of the sample holder 20 with the wafer 13 that is arranged so as to be stationary thereon is known.

In order to enable the determination also of the radial distance r as a second pole co-ordinate, the Doppler frequency shift of the reflected scattered light 15 relative to the applied measuring beam 5 is determined. For applied light in the visible range (wavelength λ of the order of magnitude of 10^{-7}m) it has a frequency ν of the order of magnitude of 10^{15} Hz in conformity with the formula:

$$\nu = c/\lambda$$

(where c = velocity of light ($3*10^8$m/s)).

This frequency value cannot be detected as an absolute value in a detector. Consequently, the frequency ν' of the scattered light 15, having been shifted only slightly with the respect to the incident measuring beam 5, cannot be determined as an absolute value either. The shifted frequency ν' is calculated such that instead of the wavelength λ = c/ν a shifted wavelength

$$\lambda' = (c-v)/\nu$$

(where v = velocity of the defect 14 that is subject to the measuring beam 5, multiplied by sin α, fig. 1, fig. 5)

must be applied; therefrom the following formula is obtained for the shifted frequency ν':

$$\nu' = c/((c-v)/\nu) = \nu/(1-v/c).$$

However, because v << c, the frequency variation is very small; it is typically in the range of kHz or 10 kHz. The frequency variation can thus be easily measured.

Because of the superposition of the reference beam 6 that oscillates at the original frequency ν and the reflected light 15 that oscillates at the shifted frequency ν', the difference between the two frequencies, that is, the so-called Doppler shift, is impressed as a modulation on the measured signal. The particle velocity v can be calculated therefrom by way of the above formula. Because the circular frequency ω of the rotating surface 8 is known, the radial distance r between the defect 14 and the center can be calculated from

$$v = \omega r$$

Because the angular frequency ω is constant, for the purpose of checking the member 13 can also be rotated a number of times for measurement in order to determine therefrom a mean value with a standard deviation. An error calculation can then be

performed. A very high accuracy is thus achieved in the determination of the position of the defect 14.

It will be evident that the device in accordance with the invention is not only suitable for the inspection of wafers 13, but also for the inspection of arbitrary other semiconductor surfaces or other surfaces, for example, substrates with thin layers, surfaces of optical or magnetic storage media, CDs, DVDs, and masks for the application of semiconductor structures, etc.